A qualitative screening tool to identify athletes with 'high-risk' movement mechanics during cutting: The cutting movement assessment score (CMAS)

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https://doi.org/10.1016/j.ptsp.2019.05.004

Manuscript Details

Manuscript number	YPTSP_2019_102_R1
Title	A QUALITATIVE SCREENING TOOL TO IDENTIFY ATHLETES WITH 'HIGH-RISK' MOVEMENT MECHANICS DURING CUTTING: THE CUTTING MOVEMENT ASSESSMENT SCORE (CMAS)
Article type	Research Paper

Abstract

Objective: To assess the validity of the cutting movement assessment score (CMAS) to estimate the magnitude of peak knee abduction moments (KAM) against three-dimensional (3D) motion analysis, while comparing whole-body kinetics and kinematics between subjects of low (bottom 33%) and high CMASs (top 33%). Design: Cross-sectional study. Setting: Laboratory. Participants: Forty-one participants (soccer, rugby, netball, and cricket). Main outcome measures: Association between peak KAM and CMAS during a 90° cut. Comparison of 3D whole-body kinetics and kinematics between subjects with low (bottom 33%) and high CMASs (top 33%). Results: A very large significant relationship ($\rho = 0.796$, $p < 0.001$) between CMAS and peak KAM was observed. Subjects with higher CMASs displayed higher-risk cutting postures, including greater peak knee abduction angles, internal foot progression angles, and lateral foot plant distances ($p \leq 0.032$, effect size = 0.83-1.64). Additionally, greater cutting multiplanar knee joint loads (knee flexion, internal rotation, and abduction moments) were demonstrated by subjects with higher CMASs compared to lower ($p \leq 0.047$, effect size = 0.77-2.24). Conclusion: The CMAS is a valid qualitative screening tool for evaluating cutting movement quality and is therefore a potential method to identify athletes who generate high KAMs and "high-risk" side-step cutting mechanics.

Keywords	Anterior cruciate ligament; knee abduction moment; injury screening; injury-risk profile

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Suggested reviewers	Anne Benjaminse, Gillian Weir

Submission Files Included in this PDF

File Name [File Type]

Cover Letter.docx [Cover Letter]

Comments from the editors and reviewers v3.docx [Response to Reviewers (without Author Details)]

Highlights-r1.docx [Highlights]

title pagev2.docx [Title Page (with Author Details)]

CMAS PTIS - FINAL- R1.docx [Manuscript (without Author Details)]

Conflict of Interest.docx [Conflict of Interest]

Ethical Statement.docx [Ethical Statement]

Supplement 1 - CMAS operational defsv3.pdf [e-Component]

Supplement 2 - Variables.docx [e-Component]

Supplement 3 - CMAS MANUALv4.pdf [e-Component]

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Research Data Related to this Submission

There are no linked research data sets for this submission. The following reason is given:
Data will be made available on request

This manuscript is original and not previously published, nor is it being considered elsewhere until a decision is made as to its acceptability by the Physical Therapy in Sport Journal Review Board. All authors have made substantial contributions to all of the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be submitted.

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-**Reviewer 1**
General:
Thank you for reviewing this interesting manuscript. Overall, the development of the CMAS is very exciting. However, the test validity should be placed in its context and limitations (test is not executed in the field where complex interaction between athlete and environment plays a role) should be acknowledged. The authors have many places (e.g. lines 128, 198-199, 233, 316, 317, 1080, 1081, 1119, 1120) where many references are mentioned. Please limit the numbers of references.

Response: Thank you for your comment. We have amended the number of citations in text throughout the manuscript, following your suggestions. Additionally, we have acknowledged the multifactorial and complex interaction of several factors regarding ACL injury. Consequently, paragraph 1 of the introduction has been amended.

Introduction:
Line 134-135: 'biomechanical and neuromuscular control deficits are critical factors that affect knee joint loading' > are these deficits causes or effects??

Response: Thank you for your comment. We have amended this paragraph, and have subsequently removed this sentence.

Line 139-155: The authors forget to put ACL injury risk in a multifactorial perspective. The end-point of movement is an hazardous movement strategy with high knee joint load. The abnormal deficits mentioned are measured in lab situations, do athletes also show this in the field ? How about an environmental context, the anticipation strategies used by an athlete used milliseconds before getting injured ? Of course, evaluating movement quality is important, but please put this in a broader perspective before zooming in.

Response: Thank you for your comment. We have now acknowledged that ACL injury risk factors are multifactorial, with a complex interaction of integral and external factors (i.e. anatomical, hormonal, environmental, shoe-surface interface, anticipation, and fatigue) during ACL injury inciting events. However, hazardous knee joint loads which are amplified with poor initial postures and mechanics, ultimately results in ACL rupture from a mechanism perspective. Yes, we agree anticipatory strategies, environment, fatigue, shoe-surface interface will also interact, but these biomechanical deficits are importantly modifiable, with the objective of qualitative screening tools to identify athletes who display these potentially 'high-risk' deficits, to subsequently enable individualised injury-risk mitigation training programmes to be developed. Therefore, this is why have concentrated focusing on the biomechanics and movement quality, because this is ultimately what the practitioner can modify.

We now state the following: "Although ACL injury-risk factors are multifactorial (74) and a complex interaction of internal and external factors (i.e. anatomical, hormonal, environmental, shoe-surface interface, anticipation, and fatigue) (8, 34, 54), a large proportion of ACL injuries are non-contact in nature during high velocity and impact sporting tasks, such as side-stepping (9, 39, 54). This occurrence can be attributed to the tendency to generate large multiplanar knee joint loading, such as knee abduction moments (KAM) and internal rotation moments (KIRM) (7, 19, 41), which increase ACL strain (4, 57, 76). These potentially hazardous knee joint loads are amplified when poor initial postures and movement is demonstrated (biomechanical and neuromuscular control deficits) during cutting (24, 34, 65), but importantly these deficits are modifiable (34, 71)."

Line 158-174: Please limit wording here (shortening section) + try to shorten introduction in general.

Response: Thank you for your comment. We have removed the list of methodological issues: "(e.g. markers sets, marker placement, soft tissue artefact, body segment inertial parameters, modelling, reference frame, normalisation, low-pass filtering cut-frequencies)"

We have done our best to be concise, but feel much of the content must remain in the introduction to help set the scene, gaps in the literature, and rationale for the study. Reviewer 2 has also specifically commented "Very nice and thorough introduction."

Line 174-185: Not sure what the purpose is of this section, as the CMAS will neither be able to do this.

Response: Thank you for your comment. We have removed the statements referring to ability to predict ACL injury. We have removed the following: "While the LESS has been validated against 3D motion analysis (65, 69), its ability to predict ACL injury is questionable with conflicting observations found (67, 76). Similarly, although the TJA and QASLS demonstrate good face validity (28, 61), there is no empirical evidence to confirm these tools can identify athletes that display high knee joint loading or ability to predict non-contact ACL injury (23, 24)."

We hope this resolves this.

Line 203: I would certainly not state this 'ecologically more valid'. Ecological validity means taking care of the interaction between person-task-environment. Even though addressing other, interesting aspects of movement in the light of ACL injury, the sidestep cutting technique as examined with the CMAS is still an isolated, preplanned movement. Please rewrite.

Response: Thank you for your comment. We have removed the term "ecologically more valid" and refer to specificity. The aim of paragraph 4 is to highlight the importance of specifically screening cutting mechanics, compared to inferring cutting mechanics from a jump-landing assessment.

Methods:
Line 446-447: Has this threshold been validated against visual observation?

Response: Thank you for your comment. Yes, this threshold was used to account for the residual noise associated with the AMTI force plates in the lab and has been confirmed against visual observation in our lab. These vertical GRF thresholds have also been used by numerous research groups including Kristianslund et al. (Oslo research group), Robinson et al. (LJMU research group), and King et al. (Sports Surgery Clinic, Dublin).

Line 504-505: How about the high-speed camera position and exit run? Was the exit run shorter than 3m. ?

Response: Thank you for your comment. As illustrated in Figure 1, the sagittal plane camera was position right of the timing gates, perpendicular to the PFC. Thus, athletes performed a 90° cut and exited 3-m from the final force plate.

Line 593: Please write confidence instead of Confidence.

Response: Thank you for your comment. This has been amended to lower case.

Discussion:
Line 982-983: Please rewrite 'high CMAS' and 'low CMAS'.

Response: Thank you for your comment. Apologies, but we do not fully understand the issue here? We have attempted to amend the sentence. We hope this resolves this, but any further clarification would be great.

Line 993-1004: A large portion of this is repetition of what has been mentioned in the introduction. Please shorten/delete.

Response: Thank you for your comment. We have deleted the following: "Side-step cutting has been identified as a key action associated with non-contact ACL injury in multidirectional sports (6, 8, 11, 19, 37, 44, 46, 60, 65, 79) due to the tendency to generate large multiplanar knee joint loading (KAMs and KIRMs) (5, 16, 39), which increases ACL strain (4, 55, 73). These potentially hazardous knee joint loads are amplified when biomechanical and neuromuscular control deficits (high-risk deficits), such as wide lateral foot plants (16, 27, 38, 48), internally rotated foot postures (initial posture) (40, 75), internally rotated hip initial postures (27, 57, 74, 75), knee abduction angles and motion (38, 40, 48, 57, 74), lateral trunk flexion (16, 26, 36, 38), and extended knee postures (13, 22, 46, 80) are demonstrated during side-step cutting."

We hope this resolves this.

Line 1033-1038: Please rewrite and eliminate the 'hint' as if CMAS will be able to predict non-contact ACL injury.

Response: Thank you for your comment. We have removed the sentences relating to predicting ACL injury, but instead we focus on the drawbacks of evaluating landing mechanics to infer cutting mechanics, and we discuss that the LESS is the only other tool to be validated against 3D.

Line 1071: Please add 'total' before 'CMAS'.

Response: Thank you for your comment. We have added 'total'.

Line 1119-1134: Do you really think the CMAS will be able to predict ACL injury ?? Is this the way such tests should be used at all ? I would be very careful with stating this. There is so many factors playing a rol in getting or not getting an ACL injury (in being at increased risk), which makes it too simple to say that one test could predict an injury. This section should be rewritten and the CMAS should but put in to a right perspective.

Response: Thank you for your comment. As stated earlier, we have removed the sentences relating to predicting ACL injury and the requirements to identify an "at-risk" threshold. We appreciate that ACL injury is multifactorial and influenced by both internal and external factors. The CMAS is simply a tool to assist in identification of poor movement quality cutting, and we appreciate that biomechanics and movement quality is only a contributing factor to a complex multifactorial mechanism of injury. However, with respect, athletes who demonstrate aberrant movement mechanics may have a potentially greater relative risk of sustaining an ACL injury, but we never state they will definitely sustain an injury.

Line 1139: Isn't pre-rotation good for knee joint load (Dempsey MSSE 2007)?

Response: Thank you for your comment. Our point regarding pre-rotation was regarding the potential difficulties in viewing lower-limb and trunk alignment because the athlete will not be perpendicular to the camera (i.e. parallax error). Research has shown that greater rotation of the foot (internal foot progression angles) increases peak KAMs (Sigward et al., 2007).

Line 1141-1148: Please reword as I am not sure I understand this sentence.

Response: Thank you for your comment. We have amended this. It now reads as follows: "It should be acknowledged that, due to the multiplanar nature of side-step cutting (7), some athletes pre-rotate towards the direction of travel during weight acceptance of the cut (77). This pre-rotation can potentially result in parallax error because the athlete is not perpendicular to the cameras which can restrict evaluations of particular CMAS criteria using the frontal plane and 45° cameras."

-Reviewer 2

General

This is a really nice study and certainly something that can be readily utilized by community level athletes and coaches. I have a few minor comments below but my main curiosity was how your ran your statistics and I wonder if you can be more specific in your methods about how you accounted for subject variability in your correlations. See my specific comments below. It seems from what you describe in your methods and present in your results, that you ran correlations and group differences on the individual trials while not accounting for inter-subject variability which is a significant statistical flaw. While I definitely understand the importance of not averaging the trials as mechanically this can wash things out if you have one trial where they had high knee moments and a higher CMAS score and another trial with low knee moments and a low CMAS score and then you average the two and get a completely different result. However, there are correct ways of entering the individual trials into a general linear model for example and then entering the participants as random factors.

This needs to be further explained and/or amended in the methods/results section before it acceptable for publication

Response: Thank you for your comment. In light of your comment regarding the pooling of trials for correlation analysis, we have consulted with a statistician and they agree with your point regarding inter-subject variability, and we have now removed the pooled correlations from the manuscript. Going forward, we have used the correlation value between the mean CMAS and mean peak KAMs for each subject (see figure 2), and we have made this clear in the statistical analyses section. Additionally, we have removed tables 3 and 4, and we have reperformed the analysis for comparisons in 3D mechanics between low and high CMAS. We now compare cutting mechanics between subjects with low and high CMASs (CMAS: top 33% and bottom 33% using subject mean data) with the results presented in Table 3. However, the primary findings are similar to the previous version of the manuscript, with subjects with high CMASs displaying higher-risk mechanics and multiplanar knee joint loads vs. subjects with lower CMASs. Finally, we did perform a general linear model which factors in CMAS, participant ID, and sex, and found it was statistically significant, with an R squared value of 0.889, and adjusted R squared of 0.763. However, in consultation with a statistician, we have decided not to include this in the manuscript because it violates the assumptions for general linear model testing because it is qualitative data and is non-parametric, and the pKAM and CMAS data were not symmetric.

Specific

Abstract

Page 2, line 87: Place $p<0.05$ within the brackets.

Response: Thank you for your comment. We have added the p value in the abstract. ($p \leq 0.047$)

Introduction

Very nice and thorough introduction.

Response: Thank you for your kind words.

Page 4, lines 198-202: No need to add this reference – but just for your interest and may add to your point. The authors compared single leg landing and unplanned sidestepping and had a similar conclusion to yours here.

Chinasee, C., Weir, G., Sasimontokul, S., Alderson, J.A., & Donnelly, C.J. (2018). A Biomechanical Comparison of Single-Leg Landing and Unplanned Sidestepping. International Journal of Sports Medicine. 39: 1-10. doi: https://doi.org/10.1055/a-0592-7422

Response: Thank you for your suggestion. We have added this reference because it further strengthens the requirement to specifically screen side-step mechanics rather than use a landing task.

Page 4, line 221: *The p and d* values in brackets might be slightly misleading here as I read that sentence as talking about the predictions and not measured vs predicted. Consider rewording or remove the p and d values in brackets.

Response: Thank you for your comment. Apologies for this coming across misleading. We have decided to remove the p and d values in the brackets.

Page 4: I wonder whether it makes more sense to make the inter- and intra- rater reliability of your variables your first hypothesis as that is the order it is presented in your results.

Response: Thank you for your comment. We have followed your suggestions and amended this section as follows: "Firstly, it was hypothesised that excellent inter- and intra-rater reliability would be demonstrated for

CMAS items. Secondly, in line with Jones et al. (43), it was hypothesised that a strong relationship would be demonstrated between CMAS and peak KAM, and the CMAS would be able to discriminate between "low" and "high" CMASs in terms of "high-risk" whole-body kinetics and kinematics."

Methods

Page 6, line 304: Were the cricket players in season at the same time as the winter sports?

Response: Thank you for your comment. In England, the sports you may be referring to as Winter Sports (i.e. rugby and soccer) competitive seasons span approximately 9-10 months. Thus, when our testing took place, all athletes from all sports were still in-season (approx. April-May). We hope this clarifies this.

Page 8, line 423-425: State that you measured completion time here and then place the times into the results section. Did athletes cut at their max speed or a pre-determined velocity? On line 441 you say that pre-contact velocity was 4.5m/s but it is not clear how you would have measured that as the timing gates are before and after the force platform. Instead state you measured velocity at foot strike or if you want to measure pre-contact velocity measure the average center of mass velocity from the penultimate toe off to cutting limb foot contact.

Response: Thank you for your comment. Firstly, apologies, we have now stated that all cutting were trials were performed as fast as possible. Secondly, in terms of calculating approach velocity we stated: "as calculated by Jones et al, (41)", but we understand this is not clear. Consequently, we have amended the section as follows: "Approach velocities were 4.5 ± 0.5 m·s-1 at initial contact (touch-down) of the PFC, by calculating the horizontal centre off mass velocity using the combined lower-limb and trunk model as recommended by Vanrenterghem et al. (77) and used previously in our laboratory (41)."

Page 8, lines 451-452: Place the filtering and events part of your analysis before you talk about calculating external joint moments as if someone was going to replicate your study step by step. Also, state that you normalized joint moments by body mass here.

Response: Thank you for your comment. Apologies for this error. We have taken on board your suggestion and moved the filtering events to the paragraph above.

Page 9, lines 517-523: It is unclear how you ran your statistics…i.e. did you correlate mean KAM and mean CMAS for each subject, mean KAM and CMAS for one trial or did you correlate KAM and CMAS for each trial with the subject coded to each trial?

Response: Thank you for your comment. We have provided a detailed response which is contained below your general comments section outlining our new statistical analyses and procedures. We have now correlated the mean CMAS and mean pKAM for each subject.

Results

Figure 2 A-C: How did you account for the subject variance in the statistical analysis here? When you run a correlation on individual trials without accounting for intra-subject variability you violate some statistical assumptions.

Response: Thank you for your comment. We have provided a detailed response which is contained below your general comments section outlining our new statistical analyses and procedures. We have now correlated the mean CMAS and mean pKAM for each subject.

Page 831-847: Again here, how were the subject variances accounted for? I completely understand why you would evaluate individual trial biomechanics variables and CMAS rather than an average as to not lose resolution but inter and intra subject variance cannot be averaged together.

Response: Thank you for your comment. We have provided a detailed response which is contained below your general comments section outlining our new statistical analyses and procedures. We have now correlated the mean CMAS and mean pKAM for each subject.

Tables 3-4: There are a lot of variables here and you haven't justified why you would measure all of them in your introduction and methods. Place into the methods section what variables you measured and provide citations for each of them.

Response: Thank you for your comment. We elude to some of these variables in paragraph 2 of the introduction. We have edited the methods (procedures section 2.4) following your suggestions. We provide a stronger justification for the additional kinetic and kinematic variables by stating the following: "Joint kinematics and GRF were also calculated using visual 3D, with Supplement 2 providing variables examined, definitions, and calculations. Briefly, the following kinetic and kinematics were examined to provide insight into potentially 'high-risk' cutting mechanics: vertical and horizontal GRF, knee flexion, rotation, and abduction angles and moments, hip rotation angle, trunk inclination angle, lateral foot plant distance, lateral trunk flexion, internal foot progression angle, and knee flexion. These kinetic and kinematics were evaluated because they have been shown to be associated with greater multiplanar knee joint loads (22, 48, 80), and have also been identified as visual characteristics of non-contact ACL injury during cutting (46, 52, 65). A more detailed rationale for investigating these variables is presented in Supplement 1. Supplement 1 contains citations for every variable examined.

Discussion

Line 993-1004: This has already been stated in the introduction. Consider removing and focus upon placing your results into context with these studies.

Response: Thank you for your comment. We have removed this section as Reviewer 1 also highlighted this.

You present a lot of biomechanics results, to quantitatively measure the differences between CMAS groups based on the items (i.e. knee abduction angle) however you don't mention this at all in your discussion. Consider acknowledging that the scoring system and your raters were able to actually assess measurable differences in kinematics/kinetics between groups as it is a nice finding.

Response: Thank you for your comment. We did discuss the differences in the kinetics and kinematics in the original manuscript in paragraph 3 of the discussion, but we do agree with your point of the raters being able to identify the abnormal movement mechanics. Consequently, we have added the following to the bottom of paragraph 3: "Krosshaug et al. (51) has highlighted the potential difficulties in estimating 3D joint kinematics based on 2D video evaluations of cutting mechanics. Conversely, the results indicate that the raters in the present study were capable of accurately evaluating and identifying aberrant lower-limb and trunk postures during cutting, as confirmed by the measurable difference in 3D kinetics and kinematics between subjects with "high" and "low" CMASs related to the CMAS scoring system (Table 3)."

It is obviously a little harder to perform but multiple studies have compared planned vs unplanned sidestepping and identified that the mechanics are quite different and the KAM is much higher with much less muscle support to counter this load. I think you should identify this as a limitation of your study.

Besier, T.F., Lloyd, D. G., Cochrane, J.L., & Ackland, T.R. (2001). External loading of the knee joint during running and cutting maneuvers. Medicine & science in sports & exercise, 33(7), 1168-1175.

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001). Anticipatory effects on knee joint loading during running and cutting maneuvers. *Medicine and science in sports and exercise*, *33*(7), 1176-1181.

Response: Thank you for your comment. We have acknowledged this as a limitation and stated the following:

"Finally, a pre-planned cutting task was used in the present study; however, results of previous research have shown that unplanned side-stepping results in greater knee loads, more abnormal mechanics, and less muscle support to counteract the greater loads compared to pre-planned side-stepping (5, 6, 11)." We feel the CMAS could be applied to unanticipated cutting.

Were all of the raters biomechanists/grad students?

Response: Thank you for your comment. Yes, they were biomechanists/ S&C/sports science graduates. We provide the specific information regarding the raters qualifications and experience in the statistical analysis section. We state the following: "The lead researcher, who has seven years' strength and conditioning and biomechanics experience, viewed and graded each trial on two separate occasions separated by 7 days, in line with previous research (24, 72) to examine intra-rater reliability. Another researcher (experienced biomechanist; 17 years' biomechanics and strength and conditioning experience), viewed and graded each trial once and these scores were compared to the lead researcher to establish inter-rater reliability. In addition, a recent sports science graduate also viewed and graded each trial once and these scores were compared to the lead researcher to establish inter-rater reliability."

Do you think your results would change if a coach did these measures?

Response: Thank you for your comment. In response, possibly; however, we can not answer this based on our data, but it is indeed something to consider in future work which we will look to do. We state the following in the limitation's sections: "Further work is required to establish agreements and reliability between different applied practitioners, such as sports rehabilitators, physiotherapists, sports coaches, in order to confirm its efficacy in the field."

Highlights:

- CMAS is a valid and reliable screening tool for evaluating side-step cutting movement quality.
- A very large significant relationship was observed between CMAS and peak KAM.
- CMAS offers practitioners a cost-effective and easily applicable field-based screening tool to identify athletes who generate high peak KAMs.
- CMAS allows practitioners to identify “high-risk” cutting mechanics in athletes
- CMAS can be used as a potential technical framework for coaching “safer” cutting.

A QUALITATIVE SCREENING TOOL TO IDENTIFY ATHLETES WITH 'HIGH-RISK' MOVEMENT MECHANICS DURING CUTTING: THE CUTTING MOVEMENT ASSESSMENT SCORE (CMAS)

Original Research

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Brief running head: Cutting Movement Assessment Score

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Abstract word count: 200 words

Manuscript word count: 4489 words

Number of tables and figures: 3 Tables, 2 Figures

3 Supplementary materials

A QUALITATIVE SCREENING TOOL TO IDENTIFY ATHLETES WITH 'HIGH-RISK' MOVEMENT MECHANICS DURING CUTTING: THE CUTTING MOVEMENT ASSESSMENT SCORE (CMAS)

ABSTRACT

Objective: To assess the validity of the cutting movement assessment score (CMAS) to estimate the magnitude of peak knee abduction moments (KAM) against three-dimensional (3D) motion analysis, while comparing whole-body kinetics and kinematics between subjects of low (bottom 33%) and high CMASs (top 33%).

Design: Cross-sectional study.

Setting: Laboratory.

Participants: Forty-one participants (soccer, rugby, netball, and cricket).

Main outcome measures: Association between peak KAM and CMAS during a 90° cut. Comparison of 3D whole-body kinetics and kinematics between subjects with low (bottom 33%) and high CMASs (top 33%).

Results: A very large significant relationship ($\rho = 0.796$, $p < 0.001$) between CMAS and peak KAM was observed. Subjects with higher CMASs displayed higher-risk cutting postures, including greater peak knee abduction angles, internal foot progression angles, and lateral foot plant distances ($p \leq 0.032$, effect size = 0.83-1.64). Additionally, greater cutting multiplanar knee joint loads (knee flexion, internal rotation, and abduction moments) were demonstrated by subjects with higher CMASs compared to lower ($p \leq 0.047$, effect size = 0.77-2.24).

Conclusion: The CMAS is a valid qualitative screening tool for evaluating cutting movement quality and is therefore a potential method to identify athletes who generate high KAMs and "high-risk" side-step cutting mechanics.

Keywords: Anterior cruciate ligament; knee abduction moment; injury screening; injury-risk profile

Highlights:

- CMAS is a valid and reliable screening tool for evaluating side-step cutting movement quality.
- A very large significant relationship was observed between CMAS and peak KAM.
- CMAS offers practitioners a cost-effective and easily applicable field-based screening tool to identify athletes who generate high peak KAMs.
- CMAS allows practitioners to identify "high-risk" cutting mechanics in athletes
- CMAS can be used as a potential technical framework for coaching "safer" cutting.

1. INTRODUCTION

Side-step lateral foot plant-and-cut actions are frequently performed movements in numerous sports (25, 84) and are also linked to decisive moments in matches, such as evading an opponent to penetrate the defensive line in rugby (tackle-break success in rugby) (84), or getting into to space to receive a pass in netball (25). Side-step cutting, however, are also actions associated with non-contact anterior cruciate ligament (ACL) injuries in sports (39, 48, 62). Although ACL injury-risk factors are multifactorial (74) and a complex interaction of internal and external factors (i.e. anatomical, hormonal, environmental, shoe-surface interface, anticipation, and fatigue) (8, 34, 54), a large proportion of ACL injuries are non-contact in nature during high velocity and impact sporting tasks, such as side-stepping (9, 39, 54). This occurrence can be attributed to the tendency to generate large multiplanar knee joint loading, such as knee abduction moments (KAM) and internal rotation moments (KIRM) (7, 19, 41), which increase ACL strain (4, 57, 76). These potentially hazardous knee joint loads are amplified when poor initial postures and movement is demonstrated (biomechanical and neuromuscular control deficits) during cutting (24, 34, 65), but importantly these deficits are modifiable (34, 71). As such, understanding the mechanics, interventions, and screening tools that can reduce ACL injury-risk factors is of critical importance.

The ability to identify athletes potentially at risk of injury is a critical step in effective ACL injury-risk reduction (26, 34). Although it is inconclusive whether screening tools can predict non-contact ACL injury (3, 27), evaluating movement quality and identifying biomechanical and neuromuscular control deficits (high-risk movement patterns) can provide important information regarding an athlete's "injury-risk profile" (33, 58, 61). These abnormal deficits include knee abduction angles (KAA) (40, 42, 50, 59, 77), lateral trunk flexion (19, 28, 38, 40), extended knee postures (16, 48, 83), and hip internal rotation (29, 59, 77, 78). This information from movement screening can subsequently be used to inform the future prescription of training and conditioning so specific deficits can be targeted through appropriate training interventions to decrease the relative risk of injury (33, 35, 61). Therefore, the inclusion of valid and reliable screening tools that assess movement quality are an important component of sports medicine and strength and conditioning testing batteries to provide an "injury-risk profile" for an athlete (33, 44).

Three-dimension (3D) motion analysis is considered the gold standard for evaluating movement kinetics and kinematics (27, 34); however, this method can be susceptible to errors, with a diverse range of data collection and analysis procedures available to practitioners which can impact outcome values, reliability, or subsequent evaluations of an athlete's biomechanical profile (12, 52). Given these methodological considerations and issues, and the fact the 3D motion analysis is expensive, time-consuming, requires expert and well trained assessors, and is usually restricted to testing one subject in laboratory setting, time- and cost-effective qualitative field-based screening tools have been developed, such as the landing error scoring system (LESS) (70, 72), tuck jump assessment (TJA) (32, 66), and qualitative analysis of single leg loading (QASLS) (2, 31), to assess lower-limb and whole-body postures associated with increased potential risk of injury (high-risk movement patterns). However, the LESS is the only screening tool of that has been validated against 3D motion analysis (69, 72).

A fundamental shortcoming of the LESS, TJA, and QASLS are these assessments generally assess landing mechanics during a vertical-orientated task. Although screening landing mechanics is indeed applicable to jump-landing sports (netball, basketball, volleyball) where the primary action associated with non-contact ACL injury is landing manoeuvres (36, 54, 79), these aforementioned assessments may lack specificity to the unilateral, multiplanar plant-and-cut manoeuvres observed when changing direction (27, 44, 61). This is particularly important when aiming to screen athletes who participate in sports such as soccer (82), handball (68), American football (39), badminton (46), and rugby (63), where directional changes are a primary action associated with-non contact ACL injuries. Furthermore, there are mixed findings whether examination of landing mechanics can identify athletes with poor cutting mechanics (1, 13, 51, 67), with evidence suggesting an athlete's mechanics and "injury-risk profile" are task dependent (13, 45, 51, 64). As such, screening side-step cutting technique, which is specific to the actions associated with non-contact ACL injuries in cutting sports (i.e. rugby, handball, soccer, American football), could be a more effective strategy for identify poor cutting movement quality in athletes, which can help inform future injury-risk mitigation training.

Unfortunately, there is a paucity of field-based cutting screening tools available for practitioners. McLean et al. (60) initially evaluated two-dimensional (2D) estimates of frontal plane knee motion during cutting against the gold standard of 3D, and found 2D estimates correlated well with side-step ($r^2 = 0.58$) and side-jump ($r^2 = 0.64$) 3D valgus angles, but poorer associations were observed with 180˚ turn knee valgus angle ($r^2 = 0.04$); thus, highlighting the difficulty in assessing 2D valgus motion in the frontal plane using a single camera during sharp CODs. Weir et al. (83) has recently demonstrated that 2D measures of dynamic knee valgus angle, knee flexion angle at foot-strike and ROM, trunk flexion ROM, when inserted in regression equations, can be used to predict 3D peak knee flexor, KAM and KIRMs during unanticipated side-steps. Despite these promising relationships, such 2D side-step screening methods are not widely adopted by practitioners and clinicians. This lack of adoption could be attributed to the 2D method requiring additional time and software to measure joint kinematics, thus potentially limiting its applicability in field settings.

In light of the issues associated with 2D analysis, Jones et al. (44) have recently developed the cutting movement assessment score (CMAS), which is a qualitative screening tool that assesses cutting movement quality and specific lower-limb and trunk characteristics that are associated with (24, 50, 83) peak KAMs (Supplement 1), such as penultimate foot contact (PFC) braking strategy, and trunk, hip, knee, and foot positioning and motions. In this preliminary study, a strong relationship between CMAS and peak KAM ($\rho = 0.633$; $p < 0.001$) was demonstrated, while moderate to excellent intra-and inter-rater agreements for all CMAS variables (Intra-rater: k = 0.60-1.00, 75-100% agreements; inter-rater: k = 0.71-1.00, 87.5-100% agreements) were observed, although lower inter-rater agreements for trunk positioning were observed (k = 0.40, 62.5% agreement). In light of these findings, the CMAS may have the potential to identify athletes displaying "high-risk" cutting mechanics but more importantly, could be used as a technical framework for coaching safer cutting mechanics. It should be noted, however, that the preliminary study contained a small sample size (n = 8 subjects, 36 trials) and must be expanded with a greater sample size to confirm its validity and reliability. Furthermore, the authors recommended an additional camera to be placed at 45° relative to the COD and using a higher video capture rate (≥100 Hz) to permit more accurate and reliable assessments for frontal and transverse plane technique deficits (i.e. trunk positioning, knee valgus).

The aim of this this study, therefore, was to assess the validity of the CMAS tool to estimate the potential peak KAMs against the gold standard of 3D motion analysis, expanding on the work of Jones et al. (44) by examining a larger sample size and using an additional camera recording at a higher sampling rate. A further aim to was to determine whether "higher-risk" movement mechanics were displayed by subjects with higher CMASs compared to subjects with lower CMASs. Firstly, it was hypothesised that excellent inter- and intra-rater reliability would be demonstrated for CMAS items. Secondly, in line with Jones et al. (44), it was hypothesised that a strong relationship would be demonstrated between CMAS and peak KAM, and the CMAS would be able to discriminate between "low" and "high" CMASs in terms of "high-risk" whole-body kinetics and kinematics.

2. METHODS

2.1 Experimental approach

This study used a cross-sectional design to determine the relationship between CMAS and peak KAMs during cutting over one session. Participants performed six 90° cuts (70-90°) whereby 3D motion and 2D video footage data were simultaneously captured to permit qualitative screening and comparisons to 3D motion data, similar to the procedures of previous research (44, 72).

2.2 Participants

Based on the work of Jones et al. (44) who determined the relationship between CMAS and peak KAM, a minimum sample size of 29 was determined from an *a priori* power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) (22). This was based upon a correlation value of ρ = 0.633, a power of 0.95, and type 1 error or alpha level of 0.05. As such, 41 athletes (28 males/13 females) from multiple sports (soccer, rugby, netball, and cricket) (mean ± SD; age: 21.3 ± 4.0 years, height: 1.75 ± 0.08 m, mass: 72.8 ± 11.8 kg) participated in this study. For inclusion in the study, all athletes had played their respective sport for a minimum of 5 years and regularly participated in one game and performed two structured skill-based training sessions per week. All athletes were free from injury and had never suffered a prior traumatic knee injury such as an ACL injury. At the time of testing, players were currently in-season (competition phase). The investigation was approved by the institutional ethics review board, and all participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved consent and parental assent documents to participate in the study.

2.3 Cutting Movement Assessment Score

Table 1 presents the CMAS qualitative screening analysis tool to estimate the magnitude of KAMs during cutting, which has been slightly modified from the preliminary investigation by Jones et al. (44) (i.e. extra description provided to some criteria). The CMAS is based on research pertaining to technical determinants of peak KAMs during 30-90° side-step cutting (24, 50, 83) and visual observations of non-contact ACL injuries (39, 48, 68). Supplement 1 contains operation definitions and a biomechanical rationale of the CMAS. If an athlete exhibits any of the characteristics in Table 1 they are awarded a score, with a higher score representative of poorer technique and potentially greater peak KAM (44).

Table 1. Cutting movement assessment score tool

Camera	**Variable**	**Observation**	**Score**
Penultimate contact			
Side / 45°	**Clear PFC braking strategy** (at initial contact) • Backward inclination of the trunk • Large COM to COP position – anterior placement of the foot • Effective deceleration – heel contact PFC	**Y/N**	**Y=0/ N=1**
Final Contact			
Front / 45°	**Wide lateral leg plant** (approx. > 0.35 m – dependent on subject anthropometrics) (at initial contact)	**Y/N**	**Y=2/N=0**
Front / 45°	**Hip in an initial internally rotated position** (at initial contact)	**Y/N**	**Y=1/N=0**
Front / 45°	**Initial knee 'valgus' position** (at initial contact)	**Y/N**	**Y=1/N=0**
All 3	**Foot not in neutral foot position** (at initial contact) Inwardly rotated foot position or externally rotated foot position (relative to original direction of travel)	**Y/N**	**Y=1/N=0**
Front / 45°	**Frontal plane trunk position relative to intended direction; Lateral or trunk rotated towards stance limb, Upright, or Medial** (at initial contact and over WA)	**L/TR/U/M**	**L/TR=2/ U = 1, /M=0**
Side / 45°	**Trunk upright or leaning back throughout contact** (not adequate trunk flexion displacement) (at initial contact and over WA)	**Y/N**	**Y=1/N=0**
Side / 45°	**Limited Knee flexion during final contact (stiff) ≤ 30°** (over WA)	**Y/N**	**Y=1/N=0**
Front / 45°	**Excessive Knee 'valgus' motion during contact** (over WA)	**Y/N**	**Y=1/N=0**
		Total Score	**0 /11**

Key: PFC: Penultimate foot contact; COM: Centre of mass; COP: Centre of pressure; WA: weight acceptance; TR: Trunk rotation; Y: Yes; N: No; L: Lateral; TR: Trunk rotation; U: Upright; M: Medial.

2.4 Procedures

The warm up, 90° cut (21), marker placement (21, 41, 44), and 3D motion analysis (21, 41, 44), and CMAS (44) procedures were based on previously published methodologies (21, 44), thus a brief overview is provided here.

Participants performed six trials of a 90° cut as fast as possible (70-90°) (Figure 1). Completion time (2.11 ± 0.14 seconds, coefficient of variation = 2.71%) was measured to standardise performance between trials, and was assessed using two sets of Brower timing lights placed at hip height (Draper, UT, USA). Marker and force data were collected over the penultimate and final foot contact using ten Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240Hz) operating through Qualisys Track Manager software (Qualisys, version 2.16 (Build 3520), Gothenburg, Sweden) and GRF's were collected from two 600 mm × 900 mm AMTI (Advanced Mechanical Technology, Inc, Watertown, MA, USA) force platforms (Model number: 600900) embedded into the running track sampling at 1200Hz, respectively.

Using the pipeline function in visual 3D, joint coordinate (marker) and force data were smoothed using a Butterworth low-pass digital filter with cut-off frequencies of 15 and 25 Hz, based on *a priori* residual analysis (86), visual inspection of motion data, and recommendations by Roewer et al. (75). Lower limb joint moments were calculated using an inverse dynamics approach (85) through Visual 3D software (C-motion, version 6.01.12, Germantown, USA) and were defined as external moments and normalised to body mass. Joint kinematics and GRF were also calculated using visual 3D, with Supplement 2 providing the variables examined, definitions, and calculations. Briefly, the following kinetic and kinematics were examined to provide insight into potentially "high-risk" cutting mechanics: vertical and horizontal GRF, knee flexion, rotation, and abduction angles and moments, hip rotation angle, trunk inclination angle, lateral foot plant distance, lateral trunk flexion, initial foot progression angle, and knee flexion angle. These aforementioned kinetic and kinematics were evaluated because they have been shown to be associated with greater multiplanar knee joint loads (24, 50, 83), and have also been identified as visual characteristics of non-contact ACL injury during cutting (39, 48, 68). A more detailed rationale for investigation of these variables is presented in Supplement 1.

The trials were time normalised for each subject to 101 data points with each point representing 1% of the weight acceptance (WA) phase (0 to 100% of WA) of the cutting task. Initial contact was defined as the instant after ground contact that the vertical GRF was higher than 20 N, and end of contact was defined as the point where the vertical GRF subsided past 20 N (42, 50, 52). The WA phase was defined as the instant of initial contact to the point of maximum knee flexion (29, 40, 41). Approach velocities were 4.5 ± 0.5 $m \cdot s^{-1}$ at initial contact (touch-down) of the PFC, by calculating the horizontal centre off mass velocity using the combined lower-limb and trunk model, as recommended by Vanrenterghem et al. (80) and used previously in our laboratory (43).

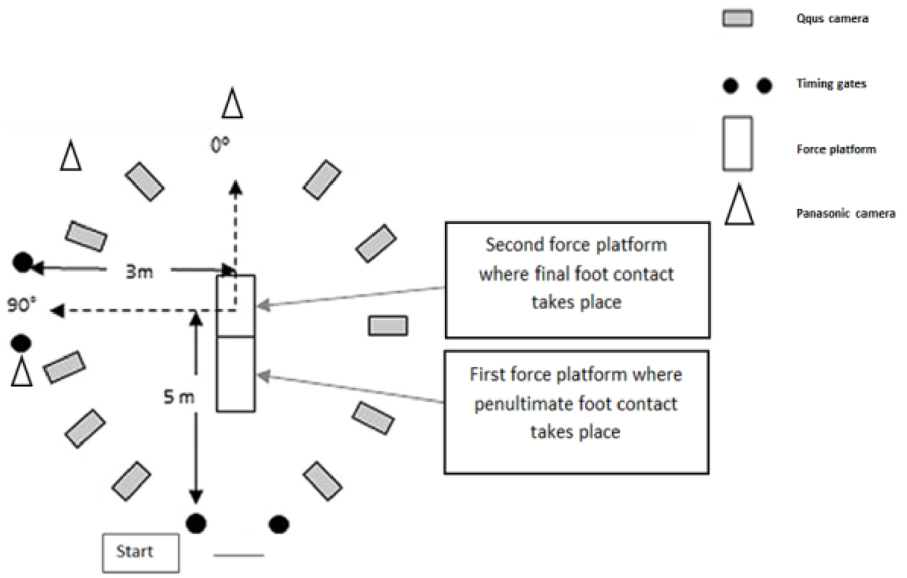

Figure 1. Plan view of the experimental set-up. The task involved subjects approaching 5-m towards turning point on 2nd force platform. At the turning point, subjects cut to the left 90° using their right limb between timing gates placed 3-m away. Marker, GRF, and 2D camera data were collected simultaneously.

2.5 Qualitative assessment: CMAS

While marker and GRF data were collected, three Panasonic Lumix FZ-200 high speed cameras sampling at 100 Hz simultaneously filmed the cutting trials. These cameras were positioned on tripods 3-m away from the force plates at a height of 0.60 m and were placed in the sagittal and frontal plane, with a camera also placed 45° relative the cut, in accordance with previous recommendations (44) (Figure 1). Video footage was subsequently viewed in Kinovea software (0.8.15 for Windows), which is free, and was used for qualitative screening using the CMAS (Table 1). This software allowed videos to be played at various speeds and frame-by-frame. The three raters were allowed to independently watch the videos as many times as necessary (23, 69), at whatever speeds they needed to score each test, and could also pause footage for evaluative purposes (23). On average, qualitative screening of one trial took ~3 minutes.

Prior to qualitative screening, all raters attended a one-hour training session outlining how to grade the cutting trials using the CMAS, and to establish and uniformly agree on low-risk and high-risk movement patterns using pilot video footage. Subsequently, the lead researcher created a manual for all raters which contained guidelines, operational definitions (Supplement 1 and 3), and example images of low-risk and high-risk motions of each screening criteria to assist CMAS screening.

2.6. Statistical analyses

Thirty-two trials were discarded due to technical issues with camera footage, 3D data, or subjects slid or missed the platform that went unnoticed during data collection, thus resulting in 214 trials (minimum 4 trials from 41 athletes) screened and used for further analysis. All statistical analyses were performed in SPSS v 24 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). To determine inter- and intra-rater reliability, 41 trials (one trial from each subject) were randomly selected by the lead researcher, similar to the procedures of previous research (44). The lead researcher, who has seven years' strength and conditioning and biomechanics experience, viewed and graded each trial on two separate occasions separated by 7 days, in line with previous research (23, 72) to examine intra-rater reliability. Another researcher (experienced biomechanist; 17 years' biomechanics and strength and conditioning experience), viewed and graded each trial once and these scores were compared to the lead researcher to establish inter-rater reliability. In addition, a recent sports science graduate also viewed and graded each trial once and these scores were compared to the lead researcher to establish inter-rater reliability.

Intra-class correlation coefficients (ICC) (two-way mixed effects, average measures, absolute agreement) for total score were determined. Intraclass correlations were interpreted based on the following scale presented by Koo and Li (49): poor (< 0.50), moderate (0.50-0.75), good (0.75-0.90), and excellent (> 0.90). For each item within the CMAS (Table 1), percentage agreements (agreements /agreements + disagreements × 100) and Kappa co-efficients were calculated. Kappa co-efficients were calculated using the formula; k = Pr(a) – Pr(e) / 1 – Pr(e), where Pr(a) = relative observed agreement between raters; Pr(e) = hypothetic probability of chance agreement, which describes the proportion of agreement between the two methods after any agreement by chance has been removed (81). The kappa co-efficient was interpreted based on the following scale of Landis and Koch (55): slight (0.01-0.20), fair (0.21-0.40), moderate (0.41-0.60), good (0.61-0.80), and excellent (0.81-1.00). Percentage agreements were interpreted in line with previous research (15, 69) and the scale was as follows: excellent (>80%), moderate (51-79%), and poor (< 50%) (15, 69).

The relationship between CMAS and the "gold standard" determination of peak KAM during the final foot contact (FFC) of the cutting task from 3D motion analysis using the means of each subject was explored using Spearman's rank correlation, with 95% confidence intervals (CI), due to the non-parametric nature of the qualitative data. Correlations were evaluated as follows: trivial (0.00-0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.00) (37). This analysis was performed using the 214 trials screened by the lead researcher.

Subjects were classified into low CMAS (bottom 33%, n = 14) and high CMAS (top 33%, n = 14) groups based on their mean CMASs. Subsequently, cutting 3D kinetics and kinematics were compared between the two groups (subject mean data) using independent sample t tests for parametric data and Mann-Whitney U tests for non-parametric data. To explore the magnitude of differences between groups, mean differences with 95% CIs and Hedges' *g* effect sizes with 95% CIs were also calculated as described previously (30), and interpreted as trivial (< 0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.0–3.99), and extremely large (≥ 4.00) (37). Statistical significance was defined $p \leq 0.05$ for all tests.

3. RESULTS

3.1 Intra- and inter-rater reliability

Excellent intra-rater reliability was observed for CMAS total score (ICC = 0.946). Intra- and inter-rater percentage agreements and Kappa coefficients are presented in Table 2. Excellent intra-rater percentage-agreements and kappa-coefficients were demonstrated for all CMAS variables (Table 2), with two variables scoring 100% agreement. For inter-rater reliability, most items displayed moderate to excellent percentage agreements (Table 2), while most items displayed moderate to good kappa coefficients between the lead researcher and experienced biomechanist. Conversely, kappa coefficients ranged from slight to good between the lead researcher and recent graduate, and most items displayed moderate to excellent percentage agreements (Table 2). Moderate inter-rater reliability was observed for CMAS total score between raters (ICC = 0.690)

Table 2. Intra- and inter-rater reliability for CMAS criteria and total score

Variable/ CMAS tool criteria	Intra-rater reliability (Lead researcher)		Inter-rater reliability - Lead research vs experienced biomechanist		Inter-rater reliability - Lead researcher vs recent graduate	
	% agreement	*k*	% agreement	*k*	% agreement	*k*
Clear PFC braking	97.6	0.940	82.9	0.633	82.9	0.633
Wide lateral leg plant	95.1	0.900	82.9	0.629	87.8	0.747
Hip in an initial internally rotated position	100.0	1.000	63.4	0.194	43.9	0.067
Initial knee 'valgus' position	90.2	0.805	75.6	0.512	75.6	0.512
Inwardly rotated foot position	100.0	1.000	80.5	0.599	90.2	0.784
Frontal plane trunk position relative to intended direction	90.2	0.805	73.2	0.551	87.8	0.767
Trunk upright or leaning back throughout contact	100.0	1.000	90.2	0.554	78.0	0.220
Limited Knee Flexion during final contact	97.6	0.932	80.5	0.431	80.5	0.381
Excessive Knee 'valgus' motion during contact	95.1	0.898	80.5	0.605	70.7	0.376
Average	96.2	0.920	78.9	0.52	77.5	0.50

Key: CMAS: Cutting movement assessment score; PFC: Penultimate foot contact

3.2 Relationships between CMAS and peak KAM

Mean ± SD from each trial of the 41 subjects were 5.1 ± 1.8 CMAS and peak KAM 1.00 ± 0.44 Nm/kg. CMASs and KAMs for males and females were 5.1 ± 1.7, 1.07 ± 0.45 Nm/kg and 5.2 ± 2.1, KAM 0.81 ± 0.35 Nm/kg, respectively**.** Figure 2 shows a linear and positive relationship between CMAS and peak KAMs. Spearman's correlation revealed a significant and very large (ρ = 0.796, 95% CI = 0.647-0.887, p < 0.001) association between CMAS and peak KAMs.

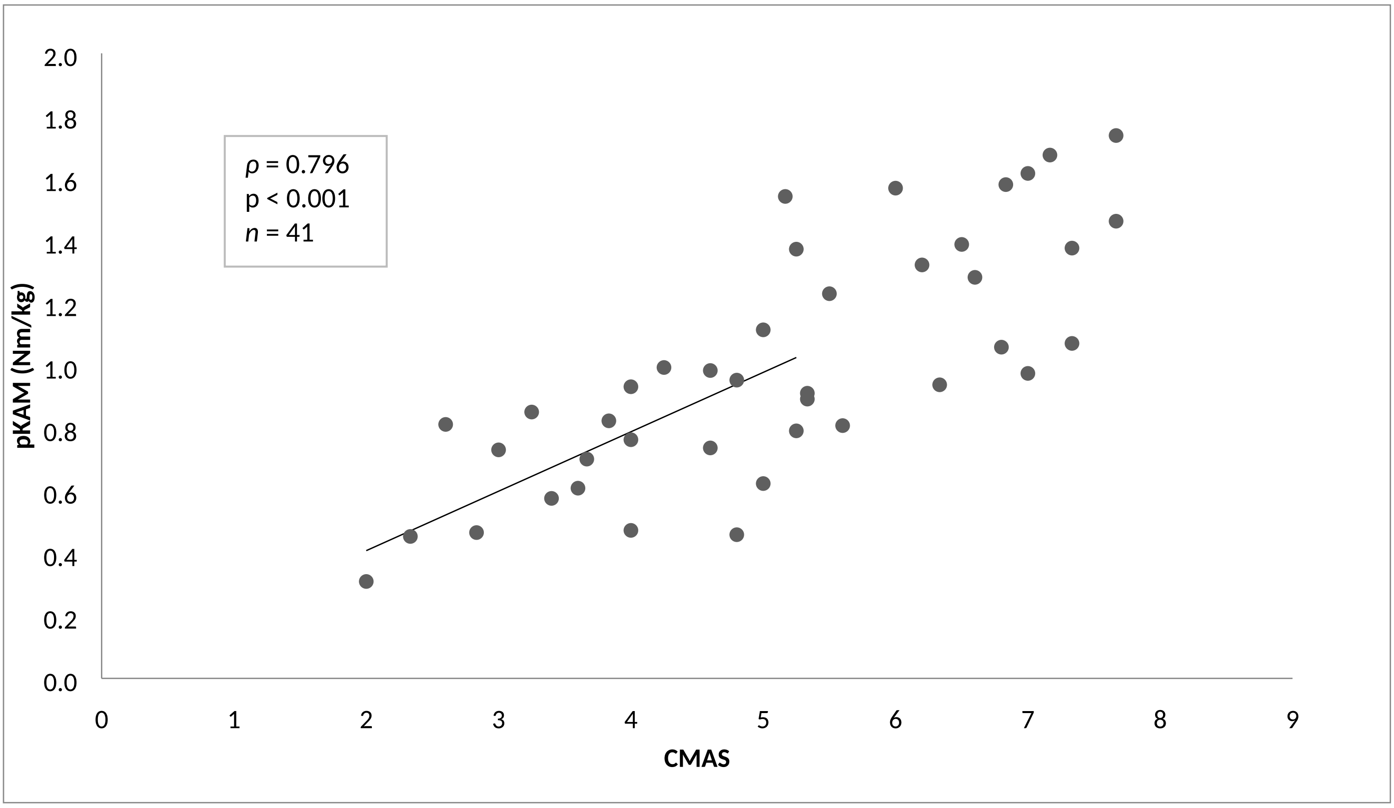

Figure 2. Relationship between CMAS and peak KAMs (pKAM) subject mean data.

3.3 Comparisons in cutting 3D kinetics and kinematics between subjects with low and high CMASs

Descriptive statistics, *p* values, and effect sizes for kinetic and kinematic measures for subjects with low and high CMASs are presented in Table 3. Subjects with higher CMASs displayed significantly greater FFC mean VBFs, HBFs, and mean HBF ratios, and greater peak knee abduction angles, internal foot progression angles, and lateral foot plant distances (Table 3), with moderate to large effect sizes. Additionally, significantly greater cutting multiplanar knee joint loads (KFMs, KIRMs, and KAMs) were demonstrated by subjects with higher CMASs compared to lower (Table 3), with moderate to very large effect sizes.

Table 3. Comparisons in 3D cutting mechanics between subjects with lower and higher CMAS containing *p* values and effect size

	Variable	Foot contact	Low CMAS (*n* = 14)		High CMAS (*n* = 14)		*p*	*g*	95% *g*		Mean difference	Mean difference 95% CI	
			Mean	*SD*	*Mean*	*SD*			LB	UB		LB	UB
	CMAS		3.34	0.70	6.95	0.63	**<0.001**	-5.29	-6.87	-3.72	-3.61	-4.13	-3.10
GRF	peak VBF (BW)	PFC	2.67	0.55	2.72	0.63	0.855	-0.07	-0.81	0.67	-0.04	-0.50	0.42
	mean VBF (BW)	PFC	0.95	0.16	0.97	0.20	0.879	-0.06	-0.80	0.68	-0.01	-0.15	0.13
	peak HBF /BW)	PFC	-1.53	0.52	-1.50	0.48	0.872	-0.06	-0.80	0.68	-0.03	-0.42	0.36
	mean HBF /BW)	PFC	-0.56	0.12	-0.53	0.14	0.617	-0.18	-0.92	0.56	-0.02	-0.12	0.07
	peak VBF (BW)	FFC	2.55	0.53	2.64	0.46	0.632	-0.18	-0.92	0.56	-0.09	-0.48	0.30
	mean VBF (BW)	FFC	1.54	0.18	1.71	0.21	**0.029**	-0.84	-1.61	-0.07	-0.17	-0.33	-0.02
	peak HBF (BW)	FFC	-1.44	0.35	-1.45	0.24	0.975	0.02	-0.73	0.76	0.00	-0.23	0.23
	mean HBF (BW)	FFC	-0.78	0.16	-0.94	0.13	**0.009**	1.03	0.24	1.82	0.16	0.04	0.27
	peak HBF ratio	both	1.03	0.35	1.06	0.39	*0.909*	-0.09	-0.83	0.66	-0.03	-0.32	0.26
	mean HBF ratio	both	1.42	0.29	1.88	0.65	***0.018***	-0.88	-1.66	-0.10	-0.45	-0.84	-0.06
Joint kinematics	peak KFA (°)	FFC	66.6	9.0	62.5	7.5	0.209	0.47	-0.28	1.22	4.0	-2.4	10.5
	KFA - IC (°)	FFC	23.1	5.1	23.6	4.9	0.766	-0.11	-0.85	0.63	-0.6	-4.5	3.3
	KFA ROM (°)	FFC	43.5	7.3	38.9	5.9	0.080	0.67	-0.09	1.43	4.6	-0.6	9.8
	peak KAA (°) (- abduction, + adduction)	FFC	-7.8	6.5	-13.4	6.6	**0.032**	0.83	0.06	1.60	5.6	0.5	10.7
	KAA - IC (°) (- abduction, + adduction)	FFC	4.3	4.8	0.6	4.7	0.052	0.75	-0.02	1.51	3.7	0.0	7.4
	KAA ROM (°)	FFC	-12.1	4.9	-14.0	5.4	0.321	0.37	-0.38	1.12	2.0	-2.0	5.9
	KRA - IC (°) (- internal, + external)	FFC	-10.7	6.9	-4.5	6.2	**0.020**	-0.91	-1.69	-0.13	-6.2	-11.3	-1.1
	peak KRA (°) (- internal, + external)	FFC	-9.6	7.4	-1.0	8.6	**0.009**	-1.04	-1.83	-0.25	-8.6	-14.8	-2.3
	Hip rotation angle - IC (°) (- internal, + external)	FFC	11.0	7.1	7.9	10.6	0.377	0.33	-0.42	1.08	3.1	-3.9	10.1
Technique	Trunk inclination angle - IC (°) (relative to vertical line, + forward, - backward)	PFC	6.8	3.9	8.1	3.4	0.361	-0.34	-1.09	0.41	-1.3	-4.1	1.6
	Trunk inclination angle - IC (°) (relative to vertical line, + forward, - backward)	FFC	17.2	31.3	10.4	6.0	0.437	0.29	-0.46	1.03	6.7	-10.8	24.2
	IFPA - IC (°) (- internal, + external)	FFC	9.0	10.2	25.5	9.3	**<0.001**	-1.64	-2.49	-0.78	-16.5	-24.1	-8.9
	Lateral trunk flexion - IC (°) (- over stance leg, + direction of travel)	FFC	-18.4	8.0	-17.6	7.3	0.794	-0.10	-0.84	0.64	-0.8	-6.7	5.2
	Lateral foot plant distance - IC (m)	FFC	-0.299	0.041	-0.336	0.044	**0.028**	0.85	0.08	1.63	0.038	0.004	0.071
Joint moment	peak KFM (Nm/kg)	FFC	3.06	0.60	3.64	0.72	**0.027**	-0.86	-1.64	-0.09	-0.59	-1.10	-0.07
	peak KRM (Nm/kg) (- internal, + external)	FFC	-0.69	0.39	-1.10	0.61	**0.047**	0.77	0.01	1.54	0.41	0.01	0.81
	peak KAM (Nm/kg) (+ abduction, - adduction)	FFC	0.73	0.27	1.37	0.28	**<0.001**	2.24	-3.18	-1.29	-0.63	-0.85	-0.42

Key: VBF: Vertical braking force; HBF: Horizontal braking force; FFC: Final foot contact; PFC: Penultimate foot contact; IC: Initial contact; BW: Body weight; KFA: Knee flexion angle; ROM: Range of motion; KAA: Knee abduction angle; KRA: Knee rotation angle; IFPA: Initial foot progression angle; KFM: Knee flexor moment; KRM: Knee rotation moment; KAM: Knee abduction moment; ES: Effect size; CMAS: Cutting movement assessment scores; Sag: Sagittal. CI: Confidence interval; LB: Lower bound; UB: Upper bounds; ES: Effect size. Note: Bold denotes statistically significant difference ($p < 0.05$) and italic denotes non-parametric.

4. DISCUSSION

The primary aim of this this study was to examine the validity and relationship between the CMAS attained from a qualitative screening tool and peak KAM quantified via 3D motion analysis. This study expanded on the preliminary work of Jones et al. (44) by using an additional camera filming at a higher sampling rate, and also investigating a larger sample size. In line with the study hypotheses, and substantiating Jones et al. (44), a very large ($\rho = 0.796$, $p < 0.001$) (Figure 2) relationship was observed between CMAS and peak KAM. Moreover, "higher-risk" cutting mechanics associated with greater knee joint loading, thus ACL injury-risk, were displayed by subjects with higher CMASs (~7) compared to subjects with lower CMASs (~3) (Table 3). The CMAS also demonstrated excellent intra-rater reliability (Table 2), and generally moderate-to-excellent inter-rater reliability (Table 2). Therefore, these findings indicate that the CMAS qualitative screening tool can be considered a reliable and valid method to identify athletes who generate high KAMs and "high-risk" cutting mechanics. This tool offers practitioners a field-based screening method which can be included in testing and screening batteries for cutting sports so "high-risk" cutting deficits can be identified and "injury-risk profiles" can be created for athletes.

In light of kinetic and kinematics (high-risk) cutting deficits associated with greater knee joint loads during side-step cutting (Supplement 1), Jones et al. (44) developed the CMAS screening tool and reported a large relationship CMAS and peak KAM ($\rho = 0.633$; $p < 0.001$). Expanding on the preliminary investigation by Jones et al. (44), the present study observed a stronger relationship between CMAS and peak KAMs ($\rho = 0.796$, $p < 0.001$, Figure 2), in a substantially greater sample size (41 vs. 8 subjects). The stronger relationships observed in the present study, compared to Jones et al. (44), could be attributed to the additional camera placed at 45° and increased sampling rate of the cameras (100 vs. 30 Hz). These additions may have permitted more accurate screening and evaluations of frontal and transverse plane deficits, such as trunk positioning and knee valgus. Nevertheless, these findings confirm that the CMAS is able to identify athletes who generate high peak KAMs, which offers practitioners a cheaper, time-efficient, and field-based applicable screening tool compared to 3D motion analysis using only three high-speed cameras and free video-analysis software.

While screening tools such as the LESS (70, 72), TJA (32, 66), and QASLS (2, 31) are useful for identifying abnormal and "high-risk" jump-landing mechanics, there is mixed evidence whether the examination of landing mechanics can identify athletes with poor cutting mechanics (1, 13, 51, 67). This issue is pertinent for practitioners who work with athletes who participate cutting dominant sports. In addition, the LESS is the only screening tool to have been validated and assessed against 3D motion analysis (69, 72), with no evidence to suggest that the TJA and QASLS is capable of identifying athletes who generate greater multiplanar knee joint loads. Conversely, in the present study, "higher-risk" cutting mechanics and greater multiplanar knee joint loads (Table 3) were demonstrated by subjects with high CMASs compared to subjects with low CMASs. These "higher-risk" mechanics included greater mean VBF and HBFs, greater KAAs, greater lateral foot plant distances, greater internal foot progression angles, and lower knee flexion ROM (Table 3), with moderate to large effect sizes. Moreover, greater multiplanar knee joint loads (knee flexion, abduction, and internal rotation moments) were also demonstrated by subjects with high CMASs compared to low, with moderate to very large effect sizes (Table 3). This finding is important because combined multiplanar loads strain the ACL to a greater extent compared to uniplanar loading (4, 57, 76). Krosshaug et al. (53) has highlighted the potential difficulties in estimating 3D joint kinematics based on 2D video evaluations of cutting mechanics. Conversely, the results indicate that the raters in the present study were capable of accurately evaluating and identifying aberrant lower-limb and trunk postures during cutting, as confirmed by the measurable difference in 3D kinetics and kinematics between subjects with "high" and "low" CMASs related to the CMAS scoring system (Table 3).

Supporting Jones et al. (44), higher CMASs were associated with greater peak KAMs (Figure 2), and "higher-risk" cutting mechanics were displayed by subjects with high CMASs (Table 3). These findings indicate that higher scores are representative of, in general, poorer cutting technique. The CMAS tool can therefore be useful for practitioners who want to screen and evaluate cutting movement quality to identify potentially "high-risk" athletes (33, 35, 58, 61), so these athletes can be targeted with biomechanical and neuromuscular informed training interventions to reduce potential injury-risk (33, 35, 61). Qualitative screening tools such as the JTA (47), LESS (20, 73), and QASLS (17) have been used to monitor the effectiveness of training interventions on jump-landing or single leg control mechanics; therefore, the CMAS could be used to monitor pre-to-post changes in cutting movement quality in response to training interventions, and is subsequently a recommended future direction of research. However, it is emphasised that lower CMASs do not necessarily equate to optimal or "safe" technique, and practitioners should not only focus on total score, but focus on the CMAS criteria where athletes scored deficits (27, 44). For example, an athlete who scores 2-3 points may still display "high-risk" cutting deficits such as knee valgus, lateral trunk flexion, limited knee flexion, or hip internal rotation and thus, would still warrant specific injury-risk mitigation training and conditioning. As such, practitioners should be cautious and are advised to look beyond the total CMAS score and use the CMAS tool to assist in the identification of potentially "high-risk" cutting deficits. The information attained from the CMAS may help inform the future prescription of training and conditioning to correct these deficits, and thus potential injury risk (33, 35, 61).

Although a plethora of investigations have focused on COD biomechanics associated with increased risk of injury and have identified a range of factors linked to knee joint loading (Table 1) (19, 28, 29, 38, 40, 41, 50, 59, 77, 78, 83), technical guidelines for coaching safer side-step cutting are limited. A unique aspect of the CMAS is that the criteria (Table 1) can be used as a technical framework for coaching safer side-step cutting which practitioners can use when working with their athletes (44).

COD technique modification has been shown to be an effective modality for reducing high-risk mechanics and knee joint loading during COD (16, 18). Consequently, using the CMAS as a screening tool and a technical framework for safer cutting could be a viable strategy which coaches and practitioners could use to identify specific "high-risk" cutting deficits (i.e. lateral trunk flexion, knee valgus) to help inform preventative COD technique modification training.

It is worth noting, however, that some of the "high-risk" cutting deficits may be needed for faster cutting performance (16, 24, 29). For example, a wide lateral foot plant is needed to generate medio-lateral propulsive force and impulse (29, 40), thus subsequent exit velocity; however, this technique concurrently elevates peak KAMs (19, 40, 50). Limited knee flexion and motion is associated with potentially shorter GCTs (16, 24), but this posture increases KAMs (50, 83), knee flexor joint loads and GRFs (16, 87), thus potential injury-risk (24). Moreover, lateral trunk flexion, from an attacking and evasive perspective, may be performed to feint and deceive opponents (10), but is a critical factor that augments potentially hazardous KAMs (19, 36). Consequently, practitioners should acknowledge the trade-off between knee joint loading (injury-risk) and performance when screening cutting mechanics, because some of the high-risk deficits demonstrated could be effective for performance. Nonetheless, practitioners should ensure that their athletes' have the physical capacity (i.e. neuromuscular control, co-contraction, and rapid force production) to tolerate the knee joint loading demands of side-steps (40, 56, 71). Further research is required to improve our understanding of the potential performance-injury conflict during cutting (24).

5. LIMITATIONS

It should be acknowledged that, due to the multiplanar nature of side-step cutting (7), some athletes pre-rotate towards the direction of travel during weight acceptance of the cut (77). This pre-rotation can potentially result in parallax error because the athlete is not perpendicular to the cameras which can restrict evaluations of particular CMAS criteria using the frontal plane and 45° cameras. Additionally, the current study only investigated a side-step cutting action; thus, the CMAS screening tool is specific to side-step cutting only. Specific screening tools must be developed and validated for assessing other COD actions, such as crossover cuts and pivots, which are also performed and associated with injury in multidirectional sport (14, 39). However, side-step cutting appears to be the predominant COD action associated with non-contact ACL injury (14, 62); therefore, highlighting the importance and inclusion of side-step cutting screening tools (CMAS) in testing batteries for athletes who participate in cutting sports, such as soccer, rugby, handball, American football, and badminton. Furthermore, the intra- and inter-rater reliability, generally, was moderate to excellent (Table 2), but limited to biomechanists and strength and conditioning coaches. Further work is required to establish agreements and reliability between different applied practitioners, such as sports rehabilitators, physiotherapists, AND sports coaches, in order to confirm its efficacy in the field. Finally, a pre-planned cutting task was used in the present study; however, results of previous research have shown that unplanned side-stepping results in greater knee joint loads, more abnormal mechanics, and less muscle support to counteract the greater loads compared to pre-planned side-stepping (5, 6, 11).

6. CONCLUSION

In conclusion, a very large significant relationship was observed between CMAS and peak KAM, and "higher-risk" cutting mechanics associated with greater knee joint loading were displayed by subjects with "high" CMASs (~7) compared to subjects with "low" CMASs (~3). As such, the CMAS is a valid and reliable screening tool for evaluating side-step cutting movement quality and offers practitioners a cost-effective and easily applicable field-based screening tool to identify athletes who generate high peak KAMs during side-step cutting. Practitioners should therefore consider including the CMAS in their fitness and testing batteries when screening and profiling athletes who participate in multidirectional sports. Equally, the CMAS allows practitioners to identify "high-risk" cutting deficits in athletes and subsequently create an "injury-risk profile". These identified deficits can be targeted and addressed through biomechanical and neuromuscular informed training interventions. Finally, the CMAS can be used as a potential technical framework for coaching "safer" cutting.

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Declarations of interest

None declared

Conflict of Interest

None declared.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical approval

Ethical Approval for the study was provided by the Ethics committee at the University of X (HSR1617-02). The work described has been carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). All subjects provided written informed consent prior to participating in the study.

Acknowledgements

The authors would like to thank all participants for partaking in this study.

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Supplement 1. Cutting movement assessment score: CMAS operational definitions and biomechanical rationale				
Suggested viewing camera	**CMAS variable**	**Observation and score**	**Operational Definition**	**Biomechanical rationale**
<u>Penultimate contact</u>				
Side / 45°	Clear PFC braking strategy (at initial contact) • Backward inclination of the trunk • Large COM to COP position - anterior placement of the foot • Effective deceleration – heel contact PFC	Y/N Y=0/ N=1	If the subject does not demonstrate a clear PFC braking strategy that emphasises large anterior placement of the foot relative to the centre of mass and does not demonstrate backwards trunk inclination (relative to a vertical straight line), then a score (+1) is awarded Practitioners may consider referring to a vertical straight line for evaluating trunk inclination.	COD is multistep action with evidence to suggest that the PFC is involved in deceleration prior to directional change, and is a 'preparatory step' (1, 20). A 'large anterior placement of the foot relative to COM and backward inclination of the trunk relative to planted foot' is considered to increase horizontal braking forces during PFC, based on research demonstrating a relationship between average horizontal GRF during PFC and peak KAMs during FFC (20). Reducing the majority of momentum during PFC, will reduce the braking requirements of the FFC, which may result in lower knee joint loads and protect against injury (19-21).
<u>Final Contact</u>				
Front / 45°	Wide lateral leg plant (approx. > 35 cm – dependent on subject anthropometrics) (at initial contact)	Y/N Y=2/N=0	If the subject demonstrates a wide lateral foot leg plant, then a score (+2) is awarded. A wide foot plant is considered as a distance > 0.35 m) between the hip and plant foot contact IC; however, this is dependent on subject anthropometrics. Practitioners assessing athletes of small stature and leg length may change this accordingly (i.e. > 0.25 m for youth athletes)	A 'wide lateral leg plant' is a major determinant of peak KAM (8, 13, 19, 24). A wide foot plant creates a GRF vector acting laterally relative to the knee, whereby greater foot plant distances creating a greater moment arm (relative to knee joint centre) and thus, KAM. Abducted hip positions are also commonly observed characteristics displayed during visual inspection of non-contact ACL injuries during COD actions (5, 12, 18, 22).
Front / 45°	Hip in an initial internally rotated position (at initial contact)	Y/N Y=1/N=0	If the subject's femur is in an internally rotated position at initial contact, then a score (+1) is awarded.	Internal hip rotation can lead to a more medially positioned knee relative to the GRF vector, thus increase moment arm distance and subsequent KAM (13, 28, 39, 41).
Front / 45°	Initial knee 'valgus' position (at initial contact)	Y/N Y=1/N=0	If the subject's knee is in a valgus (medial) position at initial contact, then a score (+1) is awarded.	'Initial knee valgus position' has been shown to be associated with peak KAM (19, 21, 24, 28, 39). An increased knee abduction angle at initial contact has an effect of placing the knee more medial to the resultant GRF vector and thus, increases the lever arm of the resultant GRF vector relative to the knee joint leading to an increased KAM. Prospective research showed greater valgus angles were associated with increased risk of non-contact ACL injury (14). Increase in knee valgus angle of 2° can lead to a 40 Nm change in valgus moment (29).
All 3	Foot not in neutral foot position (at initial contact)	Y/N	If the subject's foot is not in a neutral position (i.e. approx. 0°) and is inwardly or externally rotated at initial contact (relative to approach direction of travel), then a score (+1) is awarded	Initial foot progression angle is associated with KAM, with a neutral foot position considered the safest strategy (8, 21, 41). Internally rotated foot positions during weight acceptance can lead to a more medially positioned knee relative to the GRF vector, thus increase moment arm distance and subsequent KAM (21, 41). A

	Inwardly rotated foot position or externally rotated foot position (relative to approach direction of travel)	Y=1/N=0		neutral foot position would most likely result in forces being absorbed in the sagittal plane utilising the large knee and hip extensor musculature, which is potentially a safer strategy (21). Excessive foot external rotation increases susceptibility to eversion and pronation which could lead to knee valgus and tibial internal rotation (10, 26, 33), thus ACL loading. External rotation of the foot has also been stated as characteristics during visual inspection of non-contact ACL injuries during change of direction (18).
Front / 45°	Frontal plane trunk position relative to intended direction; Lateral or trunk rotated towards stance limb (L/TR), Upright (U) or Medial (M) (at initial contact and over WA) (use shoulder positioning as guide)	L/TR/U/M L=2/ TR = 2/ U = 1, /M=0	If the subject's trunk is laterally flexed over the stance (push-off) limb or rotated towards the stance limb at initial contact and over WA, then a score (+2) is awarded. If the subject's trunk is upright (vertical relative to straight line), then a score (+1) is awarded. If the subject's trunk is medial (leaning towards the intended direction of travel), then no score is awarded. Practitioners may consider referring to a vertical straight line and use shoulder position as an indicator.	The trunk contains approx. half of the body's mass, and during cutting the entire body's mass must be balanced and supported on one leg, thus trunk control and positioning is a critical factor influencing knee joint loads (15, 16, 30). Lateral trunk flexion (8, 17, 19) or trunk rotation (8, 11) towards stance limb are major determinants of peak KAM. A laterally flexed trunk or rotated trunk towards the planted leg side shifts the athlete's weight laterally creating a laterally directed force vector, increasing the moment arm relative to the knee joint and thus, KAMs. Prospective research has shown deficits in trunk control and proprioception are associated with increased risk of non-contact ACL injury (48, 49). Lateral trunk flexion over plant leg also a commonly observed visual characteristic of non-contact ACL injuries during plant-and cut manoeuvres and landing (16, 22, 42).
Side / 45°	Trunk upright or leaning back throughout contact over whole contact (not adequate trunk flexion displacement) (at initial contact and over WA)	Y/N Y=1/N=0	If the subject's trunk is upright or leaning back throughout weight (i.e. appears limited hip flexion) acceptance and push-off during the FFC and does not go through an adequate range of trunk-flexion displacement, then a score (+1) is awarded.	Trunk inclination (leaning back or upright) with minimal trunk flexion displacement during weight acceptance may increase the overall knee joint load due an increased lever arm of the trunk relative to the knee and increasing the COM distance from the base of support (37). Some trunk flexion allows generation of hip moments to help absorb the GRF during weight acceptance and thus, may lower KAMs (21). Increasing hip increasing hip flexion and promoting a hip dominant strategy are involved GRF attenuation (38, 40, 47), energy dissipation (35, 46), reducing loading rates (40) and reducing knee joint loads (32, 35, 36, 40) during high impact tasks. Increasing hip flexion increases the moment arm distance at the hip which creates a greater hip flexor moment (utilising hip extensor musculature). This can have the effect of unloading the knee by more evenly distributing loading proximally up the lower-limb chain (21, 35, 36, 40), thus reducing the demands for the knee.
All 3	Limited knee flexion during final contact (stiff) ≤ 30˚	Y/N Y=1/N=0	If the subject's knee goes through limited knee flexion (approximately ≤ 30˚) over weight acceptance appears 'stiff', then a score (+1) is awarded.	Stiffer weight acceptance strategies can increase impact GRFs (7, 9, 50), and greater GRFs are associated with increased KAMs (39, 41). Less knee flexion is also associated with greater KAMs (24, 44). Furthermore, extended knee positions with high anterior tibial loading and shear force can also increase ACL strain (2, 3, 27, 45). Extended knee positions are also commonly observed characteristics of non-contact ACL injury during directional changes and landing (4-6, 12, 18, 22, 23, 25, 31, 34, 43).

Front / 45°	Excessive knee 'valgus' motion during WA	Y/N Y=1/N=0	If the subject's knee demonstrates visible valgus motion during weight acceptance, then a score (+1) is awarded.	Knee valgus motion during FFC is considered because it is a key indicator of ACL injury risk (14), and can contribute to large front plane knee joint loading. Dynamic knee valgus positions are also commonly observed characteristics of non-contact ACL injury during directional changes and landing (5, 6, 12, 18, 22, 23, 25, 34, 42, 43).
Key: PFC: Penultimate foot contact; FFC: Final foot contact; KAM: peak Knee abduction moment: ACL: Anterior cruciate ligament; IC: Initial contact; WA: Weight acceptance; GRF: Ground reaction force. Y: Yes; N: No; L: Lateral; TR: Trunk rotation; U: Upright; M: Medial.				

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Supplement 2. Definitions and calculations for kinetic and kinematic variables examined during cutting

	Variable	Foot contact	Abbreviation	Definition or calculation
Sagittal plane knee joint moments	Peak knee flexor flexor moment	FFC	HFM	Peak external joint moments during weight acceptance of FFC using inverse dynamics.
Sagittal plane joint angles	knee flexion angle	FFC	KFA	Derived from the following order of rotations: flexion (+)/extension (-)
Frontal plane injury risk parameters	Peak knee abduction moments	FFC	KAM	Peak external knee abduction moment (+ abduction/- adduction) during weight acceptance phase of FFC using inverse dynamics.
	Knee abduction angle	FFC	KAA	Knee abduction angle (-) during weight acceptance phase of final contact /adduction (+)
Transverse plane injury risk parameters	Peak knee rotation moment	FFC	KRM	Peak external knee rotation moment (+ external/- internal) during weight acceptance phase of final contact using inverse dynamics
	Knee rotation angle	FFC	KRA	Knee rotation angle (- internal/ + external) during weight acceptance phase of FFC
GRF	Peak vertical braking force (Fz)	PFC and FFC	VBF	Peak normalised vGRF (Fz) value during weight acceptance
	Mean vertical braking force (Fz)	PFC and FFC	Mean VBF	Average normalised vGRF (Fz) during weight acceptance
	Peak horizontal braking force (Fx)	PFC and FFC	HBF	Peak normalised hGRF (Fx) value during weight acceptance
	Mean horizontal braking force (Fx)	PFC and FFC	Mean HBF	Average normalised hGRF (Fx) during weight acceptance
	Braking force ratio	Between the two contacts	-	FFC braking force / PFC braking force
Trunk variables	Lateral Trunk flexion	FFC	-	Angle of trunk relative to vertical line perpendicular to the pelvis: (0˚) upright / (+) trunk flexion away from plant leg/ (-) trunk flexion towards plant leg
	Trunk inclination angle	PFC and FFC	-	Angle of trunk relative to a vertical straight-line straight line, (+) forward trunk lean/ (-) backward trunk lean
Hip, pelvis, and foot	Hip rotation angle	FFC	-	Femur internally rotated (-)/ external rotation (+)
	Lateral foot plant distance	FFC	-	Lateral distance from initial foot contact of foot COM to proximal end of pelvis – for cutting
	Initial foot progression angle	FFC	IFPA	Angle of foot progression relative to lab coordinate system configuration/ original direction: straight (0°)/inward rotation (+)/outward rotation (-) angle (°)

Key: PFC: Penultimate foot contact; FFC: Final foot contact; COM: Centre of mass; COD: Change of direction; IC: Initial contact; GRF: Ground reaction force; vGRF: Vertical GRF; hGRF: Horizontal GRF;

Supplement 2. CMAS MANUAL

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
Penultimate contact			
Side / 45°	**Clear PFC braking strategy** (at initial contact) • Backward inclination of the trunk • Large COM to COP position – anterior placement of the foot • Effective deceleration – heel contact PFC	**Y/N**	**Y=0/ N=1**
Final Contact			
Front / 45°	**Wide lateral leg plant** (approx. > 0.35 m – dependent on subject anthropometrics) (at initial contact)	**Y/N**	**Y=2/N=0**
Front / 45°	**Hip in an initial internally rotated position** (at initial contact)	**Y/N**	**Y=1/N=0**
Front / 45°	**Initial knee 'valgus' position** (at initial contact)	**Y/N**	**Y=1/N=0**
All 3	**Foot not in neutral foot position** (at initial contact) Inwardly rotated foot position or externally rotated foot position (relative to original direction of travel)	**Y/N**	**Y=1/N=0**
Front / 45°	**Frontal plane trunk position relative to intended direction; Lateral or trunk rotated towards stance limb, Upright or Medial.** (at initial contact and over WA)	**L/TR/U/M**	**L/TR=2/** **U = 1,** **/M=0**
Side / 45°	**Trunk upright or leaning back throughout contact** (not adequate trunk flexion displacement) - (at initial contact and over WA)	**Y/N**	**Y=1/N=0**
Side / 45°	**Limited Knee Flexion during final contact (stiff) ≤ 30**° (over WA)	**Y/N**	**Y=1/N=0**
Front / 45°	**Excessive Knee 'valgus' motion during contact** (over WA)	**Y/N**	**Y=1/N=0**
		Total Score	**0 /11**

Key: PFC: Penultimate foot contact; COM: Centre of mass; COP: Centre of pressure; WA: weight acceptance; TR: Trunk rotation; Y: Yes; N: No; L: Lateral; TR: Trunk rotation; U: Upright; M: Medial.

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
<u>Penultimate contact</u>			
Side / 45°	**Clear PFC braking strategy** (at initial contact) • Backward inclination of the trunk • Large COM to COP position – anterior placement of the foot • Effective deceleration – heel contact PFC	Y/N	Y=0/ N=1

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
Final Contact			
Front / 45°	**Wide lateral leg plant** (approx. > 0.35 m – dependent on subject anthropometrics) (at initial contact)	Y/N	Y=2/N=0

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
<u>Final Contact</u>			
Front / 45°	**Hip in an initial internally rotated position** (at initial contact)	**Y/N**	**Y=1/N=0**

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
<u>Final Contact</u>			
Front / 45°	**Initial knee 'valgus' position** (at initial contact)	**Y/N**	**Y=1/N=0**

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
Final Contact			
All 3	**Foot not in neutral foot position** (@ initial contact) Inwardly rotated foot position or externally rotated foot position (relative to original direction of travel)	**Y/N**	**Y=1/N=0**

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
<u>Final Contact</u>			
Front / 45°	**Frontal plane trunk position relative to intended direction; Lateral or trunk rotated towards stance limb, Upright or Medial.** (at initial contact and over WA)	L/TR/U/M	L/TR=2/ U = 1, /M=0

L | TR | U | M

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
Final Contact			
Side / 45°	**Trunk upright or leaning back throughout contact** (not adequate trunk flexion displacement) - (at initial contact and over WA)	Y/N	Y=1/N=0

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
<u>Final Contact</u>			
Side / 45°	**Limited Knee Flexion during final contact (stiff) ≤ 30**˚ (over WA)	**Y/N**	**Y=1/N=0**

Yes

No

Table 1. Cutting movement assessment score tool

Camera	Variable	Observation	Score
<u>Final Contact</u>			
Front / 45°	**Excessive Knee 'valgus' motion during contact** (over WA)	Y/N	Y=1/N=0

Yes

No